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Experimental Verification of a Model of Heat Transfer Through Windows

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ABSTRACT

A procedure has been developed for calculating the one-dimensional heat flux through complex window systems. A computer program embodying this procedure (WINDOW 2.0) is available to the public. The window may consist of multiple glass or plastic layers, separated by gas-filled spaces. Gases other than air may fill the space between solid layers, and the layers may have low-emissivity coatings. Measurements from five different manufacturers and researchers of the overall thermal conductance of various window systems confirm the validity of this model for a range of temperatures and layer spacings less than 3 cm (1.2 in). A list of U-values and shading coefficients is given for a representative group of windows.

INTRODUCTION

An earlier paper described in detail a model for calculating the heat flux through windows (Rubin 1982a). One purpose of this paper is to report major revisions to that model. Another purpose is to validate the model via comparisons to measurements of the overall thermal conductance of complete window systems. A computer program embodying this model is available to the public. The latest version, WINDOW 2.0, has a number of technical improvements, as well having a more flexible format and easier operation than version 1.0. WINDOW 2.0 is written in standard Fortran and operates on a minicomputer and personal computers. The personal computer version does not require a math co-processor or a graphics card.

Since the introduction of low-emissivity coatings, the number of window variations has greatly increased. Other developments such as gas fills threaten to multiply this number. Our method is intended to provide a consistent standard for comparing the thermal performance of these windows. The model yields a one-dimensional temperature profile of the window together with the heat-transfer coefficients. The commonly used figures of merit, such as U-value (conductance) and ASHRAE shading coefficient, are calculated from this basic information.

In the next section we outline the calculation procedure and describe the major modifications in going from WINDOW 1.0 to 2.0. Then we compare the results of this program to experimental conductance data obtained by hot-box and hot-plate measurements. Finally we propose modifications to improve accuracy and extend the capabilities of the program. Table 1 presents results for many glazing systems.

CALCULATION PROCEDURE

Rubin (1982a) describes, in detail, the theoretical foundation of this calculation procedure. A window, as defined in this procedure, consists of a series of plane-parallel transparent solid layers separated by gas spaces. The positions of the nodes in the numerical solution are dictated by the thickness and thermal conductivity of these layers. A one-dimensional temperature profile is assumed across the center of the window. The various heat transfer coefficients are evaluated in terms of these temperatures from fundamental radiative theory or from semiempirical correlations in the case of convection. The final temperature distribution is refined iteratively by a finite-difference method until the desired accuracy is obtained. Although this procedure is too tedious for hand calculation, it is straightforward on a computer and can be generalized to an arbitrary number of nodes.

Ideally, a multidimensional model would be used to explicitly account for the finite extent of the window and the characteristics of the frame. In practice, however, the geometry of the window and the thermal boundary conditions are too complex to specify, even if they are known, for comparisons of window products. The use of multi-dimensional models should be reserved for more specific studies of perimeter effects. For example, such models can be used to provide effective thermal conductances for frames that can be used in an area-weighted average. WINDOW 2.0 can accept as input the fractional frame area and the effective conductance of the frame. Hartmann et al. (1978) provide conductances for a small number of frame types. Until we can provide more accurate measured effective thermal conductivities, the conductance of the frame cross section is used.

In simple calculations of window conductance, it is usually assumed that glass layers are completely opaque and air completely transparent to radiation in the thermal infrared. In this case, only the emissivity of the glass enters the calculation. Some windows may have partially infrared-transparent solid layers, such as thin polyester films (Rubin 1981) or aerogels (Rubin 1983). The radiative heat balance is then complicated by the increased number of direct pathways for radiative transfer. This, however, is only a mathematical complexity, which is handled within the framework of WINDOW 2.0 as in Rubin (1982a) by a set of inhomogeneous linear equations.

The convective coefficients, on the other hand, can be neatly decoupled between solid layers, but are not always well defined or reliable. For the enclosed gas space of a multiple-layer window, we now use the correlation of El Sherbiny et al. (1982) between Nussalt number, Nu, and Rayleigh number, Ra:

$$Nu = [\,1+ (0.0303Ra^{0.402})^{11}]^{1/11} \tag{1}$$

This correlation replaces that of DeGraff and van der Held (1952) in our original model, because it derives from experiments specifically designed to simulate a window, giving better agreement with measurements of heat transfer rates. Other expressions are also given in this study for a tilted slot (as in a skylight); WINDOW 2.0 will incorporate these additional correlations in the future. Gases other than air can be treated by replacing the appropriate physical constants in the Rayleigh number.

Previously, solar-optical properties were provided as the overall transmittance of the window and the absorptance of each layer seen as part of the window (i.e., counting all interreflection and resulting secondary absorption). This form of the data is required for calculating solar heat gain directly. A more flexible set of input data (which is usually available in product literature) is the transmittance and reflectance of the individual glazing elements. The following simplified formulation of our more general method (Rubin 1982b) can be used to translate the transmittance and reflectance of isolated layers to overall transmission and effective absorption data.

Consider a window composed of n absorbing solid layers separated by gas layers, where each solid layer may be a homogeneous material like glass or a coated substrate. Each group of layers i through j has transmittance T_{ij}, outside (front) reflectance R^f_{ij}, and inside (back) reflectance R^b_{ji}. Given the properties of each layer, T_{ii}, R^j_{ii}, and R^j_{ii}, the following recursion relations can be used to predict the overall transmittance $T \equiv T_{1,n}$ and reflectance $R \equiv R^f_{1,n}$:

$$T_{ij} = T_{ji} = \frac{T_{i,j-1}\, T_{jj}}{1-R^f_{jj}\, R^b_{j-1,i}} \tag{2}$$

$$R^f_{ij} = R^f_{i,j-1} + \frac{T^2_{i,j-1}\, R^f_{jj}}{1-R^f_{jj}\, R^b_{j-1,i}} \tag{3}$$

$$R^b_{ji} = R^b_{i,j-1} + \frac{T^2_{jj}\, R^b_{j-1,i}}{1-R^f_{jj}\, R^b_{j-1,i}} \tag{4}$$

If the absorptions in the ith element standing alone from front and back are $A^f_i = 1 - T_{ii} - R^f_{ii}$ and $A^b_i = 1 - T_{ii} - R^b_{ii}$, then the effective absorption in the ith layer in the window is

$$\overline{A}_i = \frac{T_{1,i-1} A^f_i}{1 - R^f_{i,s} R^b_{i-1,1}} + \frac{T_{1,i} R^f_{i+1,s} A^b_i}{1 - R^b_{i,1} R_{i+1,s}} \tag{5}$$

The above expressions are only approximately valid because polarizations and wavelength dependencies have been averaged for the properties of the individual layers. With the information usually available, polarization cannot be considered, but a two-waveband model (visible and solar infrared) will often be possible. The properties of common glazing materials, both coated and uncoated, as well as a multiband model option will be available from the menu in the next version of WINDOW.

RESULTS

Experimental measurements of the overall thermal conductance were obtained from a variety of sources. Hot-box measurements were made at our laboratory by Klems (1979), and hot-plate measurements were obtained from three manufacturers (see Acknowledgements) and from Glaser (1977).

In the case of the guarded hot-plate, the window is sandwiched between liquid-heated and liquid-cooled metal plates. Heat-flow sensors and the known temperatures of the thermostatically controlled fluids give the surface-to-surface conductance. Standard West German indoor and outdoor film coefficients (combined radiative and convective) of 1.41 and 4.40 $Btu/h \cdot ft^2 \cdot F$ (8 and 25 $W/m^2 \cdot C$), respectively, were then added in series to the measured value. In all cases, the procedure followed West German DIN Standard 52612.

The above procedure is somewhat unrealistic, because the temperatures of exterior surfaces of the window are maintained constant. In the hot-box technique, the surfaces are not in contact with isothermal plates but with heated air on one side and cooled air on the other. The amount of power supplied to the heater gives the heat flux after correcting for frame and skin effects. The effect of free and/or forced convection can be determined by this method. For more details, see Klems (1979).

We now compare the measured conductances to values calculated using WINDOW. These test windows may have two, three, or four layers of glass and/or infrared-transparent polyester film; some surfaces have low-emissivity coatings, and the gaps may be filled with either air or argon. Figures 1 and 2 show the comparison to the hot-plate measurements as a function of gap width and outside temperature, respectively. Figure 3 similarly compares the hot-box data to calculated values as a function of gap width.

In Figure 1, most of the values calculated using WINDOW fall within the experimental error of the measurements. That we consistently underpredict the results of Glaser for double glazing with an $\epsilon =$ 0.065 film is the most notable exception. Although on a firm theoretical footing, the radiation component of the calculation may be thrown off by incorrectly reported values of radiation properties. The reported value of $\epsilon = 0.065$ by Glaser is unusually low, leading us to speculate that it may have been incorrectly measured or that its properties may have degraded due to exposure. With this same exception, data taken over a range of temperatures (Figure 2) also show excellent agreement with calculations.

The hot-box data shown in Figure 3 extend the results for double glazing to much larger gap widths than in Figures 1 and 2. Here again, theory and experiment agree well for gap widths less than a few centimeters. Beyond this point, calculated values rise slowly while experimental results remain approximately constant, but we still see good agreement. This discrepancy is not surprising, because the semiempirical correlation of El Sherbiny was fit to data in the smaller range. Although based partly on theory, there is no guarantee that this correlation will be valid for large spacing. The fit between theory and experiment for the units with one and two plastic layers is reasonable given our uncertainty in the IR properties of the material used.

Most commercial windows are manufactured with gaps of less than 0.75 in (2 cm) so that WINDOW may be used with confidence in these cases. Many manufacturers have speculated on the possibility of making windows with very wide air gaps. This topic therefore deserves further experimental study. For the present we can say that the wider spacing will probably not result in a significant decrease in conductance.

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TABLE 1
U-Values of Highly Insulating Windows at ASHRAE Standard Winter
Design Conditions in $Btu/h{\cdot}ft^2{\cdot}F$ ($W/m^2{\cdot}C$)
As Calculated by WINDOW 2.0

Window Design* OUTSIDE——INSIDE	Gas Fill	Gap Width $\frac{1}{4}$" (6.4 mm)	Gap Width $\frac{1}{2}$" (12.7 mm)
Double Glazing G—G E = 0.72	Air	0.58 (3.27)	0.50 (2.85)
	Ar	0.52 (2.97)	0.47 (2.66)
	Kr	0.46 (2.63)	0.46 (2.62)
$G_e - {}_eG$ e = 0.35 E = 0.21	Air	0.47 (2.66)	0.36 (2.06)
	Ar	0.39 (2.21)	0.31 (1.77)
	Kr	0.30 (1.69)	0.30 (1.71)
$G - {}_eG$ e = 0.15 E = 0.15	Air	0.45 (2.56)	0.34 (1.94)
	Ar	0.37 (2.09)	0.29 (1.62)
	Kr	0.27 (1.53)	0.27 (1.56)
$G - {}_eG_e$ e (#3 surface) = 0.15 e (#4 surface) = 0.35 E = 0.15	Air	0.39 (2.21)	0.30 (1.70)
	Ar	0.32 (1.83)	0.25 (1.44)
	Kr	0.24 (1.37)	0.24 (1.39)
$G - {}_eG - G$ e = 0.15 E = 0.15, 0.72	Air	0.33 (1.88)	0.24 (1.38)
	Ar	0.27 (1.54)	0.21 (1.17)
	Kr	0.20 (1.15)	0.20 (1.11)
$G - {}_eG - {}_eG$ e = 0.15 E = 0.15, 0.15	Air	0.29 (1.62)	0.19 (1.07)
	Ar	0.22 (1.26)	0.15 (0.85)
	Kr	0.15 (0.86)	0.14 (0.79)
$G - {}_eG - {}_eG - G$ e = 0.15 E = 0.15, 0.15, 0.72	Air	0.23 (1.32)	0.15 (0.88)
	Ar	0.18 (1.04)	0.13 (0.72)
	Kr	0.13 (0.73)	0.11 (0.65)

*G denotes a glazing layer; The subscript "ϵ" denotes a low-emissivity coating; e is the hemispherical emittance of the low-emissivity surface(s); E is the effective emittance $(1/\epsilon_1 + 1/\epsilon_2 - 1)^{-1}$ of the gap(s).
IR transmittance of all glazing layers are taken to be 0; emittance of an uncoated glass surface is 0.84.

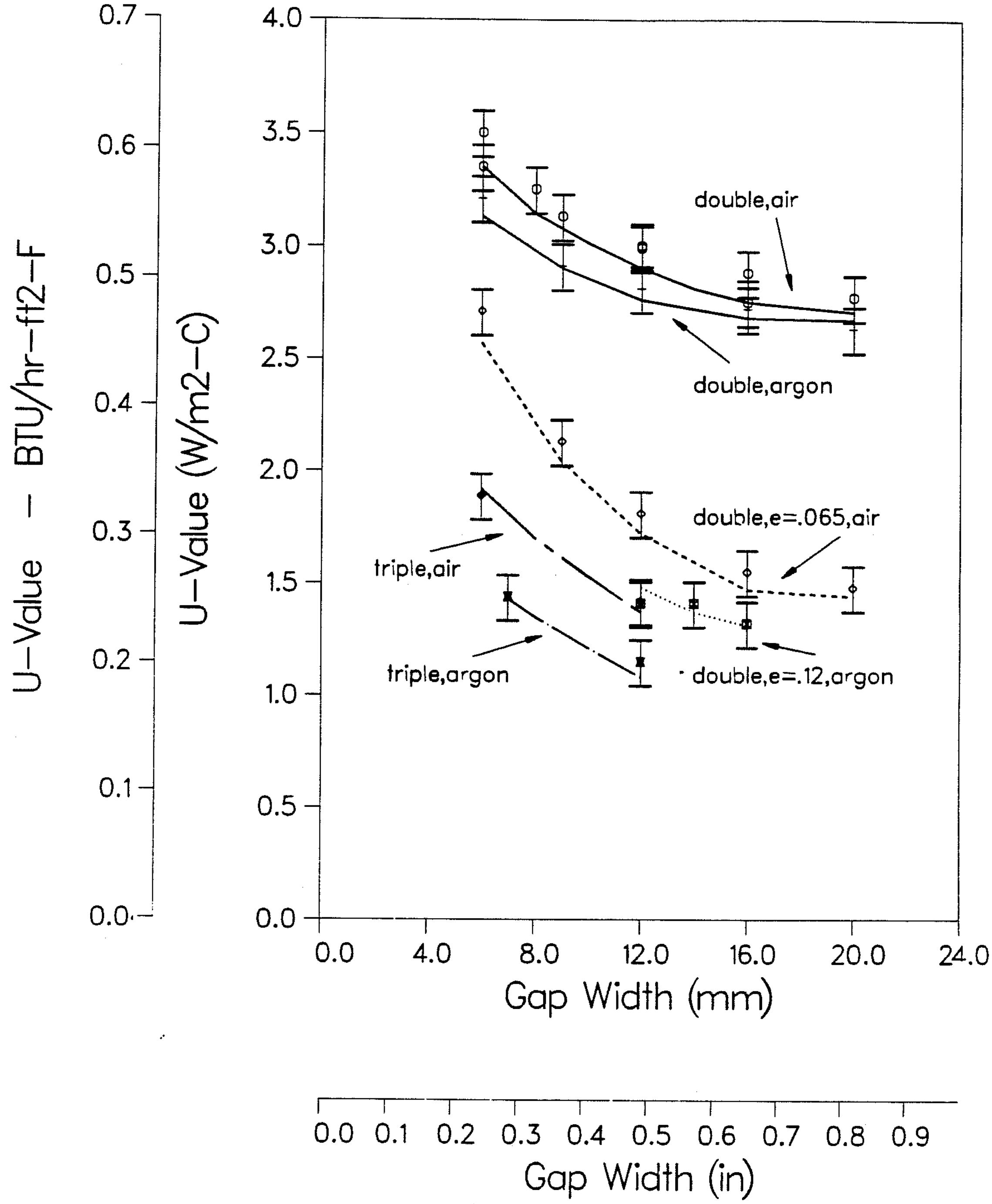

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Figure 1. Comparisons of WINDOW 2.0 calculations with experimental data from three manufacturers and Glaser as a function of gap width.

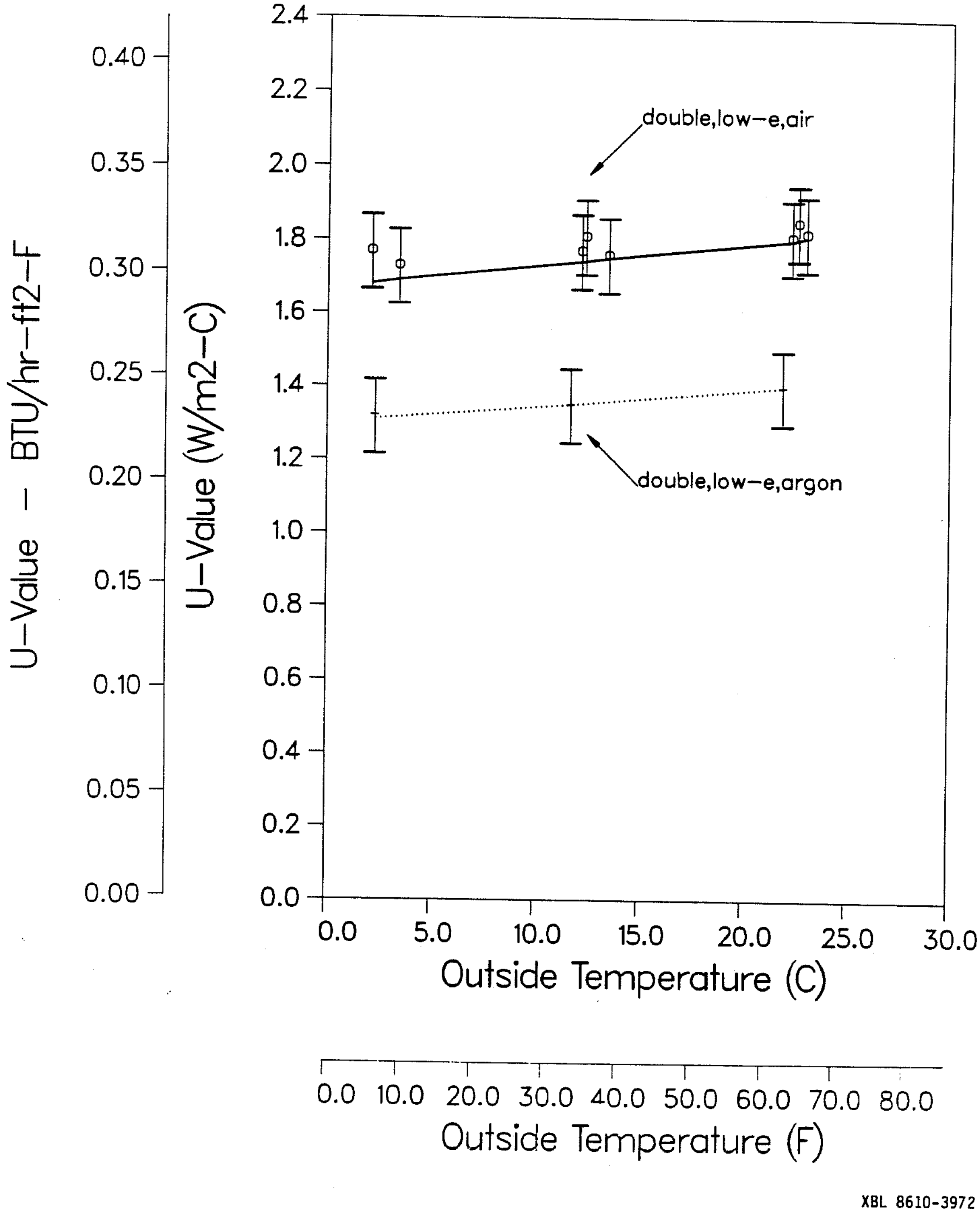

Figure 2. Comparison of WINDOW 2.0 calculations with experimental data from one manufacturer as a function of outdoor temperature. The inside temperature is 10°C (18 F) higher than the outside temperature.

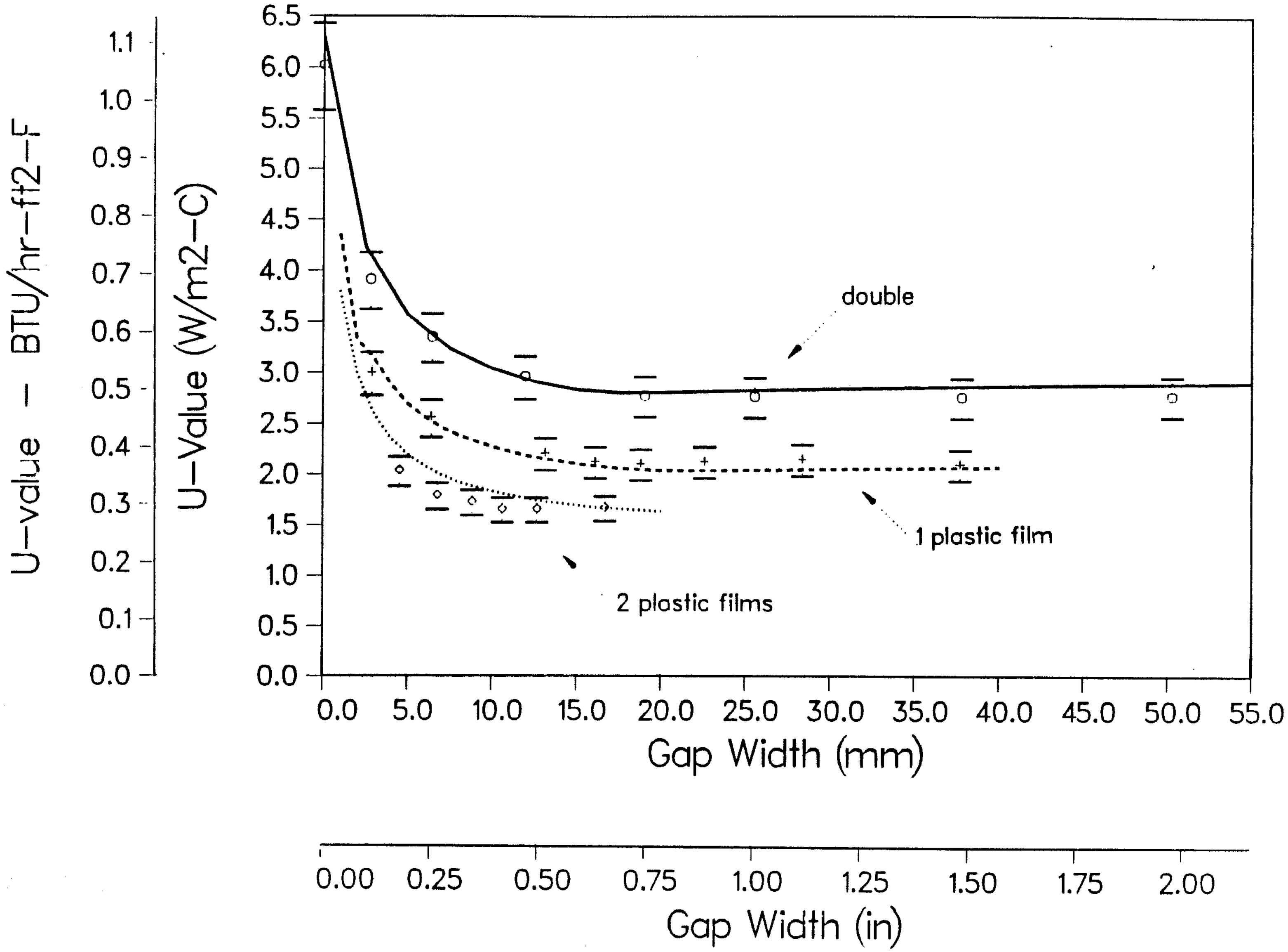

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Figure 3. Comparison of WINDOW-2.0-calculated U-values as a function of gap width with the hot-box data from Klems, where T_o = 0°C, T_i = 21°C, and wind speed is 6/7 m/s.